NRL Report 8360

The Contribution of Navigation Technology Satellites to the Global Positioning System

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Pseudo-Random Noise Subsystem Assembly (PRNSA)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Navigation Technology Satellites, developed by the Naval Research Laboratory, have been provided as a vehicle for the design and test of basic satellite navigation technology currently in use in the NAVSTAR Global Positioning System (GPS). Two satellites, TIMATION I and II, were flown in 1967 and 1969 to demonstrate the concept of using synchronized clocks to provide time ranging for navigational purposes. Navigation Technology Satellite 1 (NTS-1), flown in 1974, introduced a rubidium atomic clock, and NTS-2, flown in 1977, introduced a cesium clock. Both clocks provided increasingly

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20. Abstract (Continued)

superior navigation accuracy. A hydrogen maser clock for even better performance and reduced dependency on ground updating is being developed. In addition to the clock development the technology satellites have tested the effect of the radiation environment, the use of retroreflectors for laser tracking, and improved solar cells and batteries. As a result of NTS-2 tests the Air Forces's Space and Missile Systems Organization (SAMSO) program office stated that the NAVSTAR GPS concept had been successfully validated.

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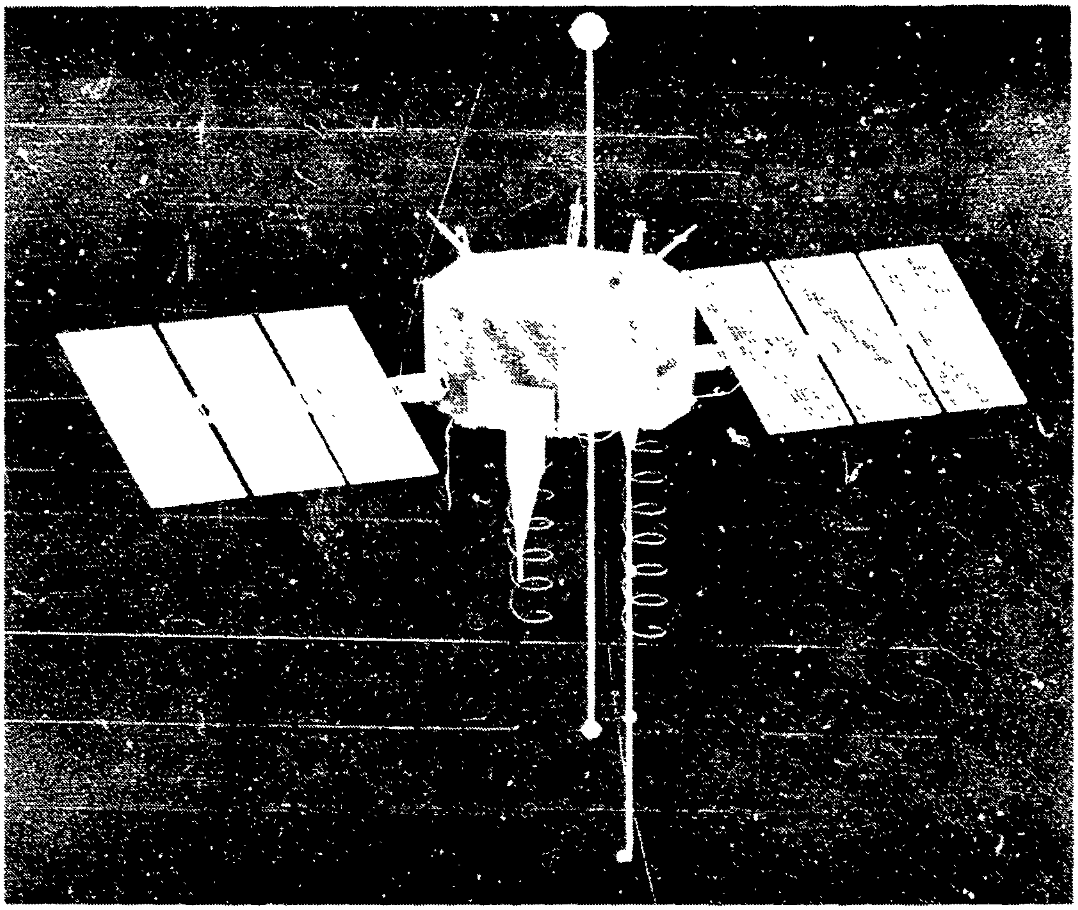

THE CONTRIBUTION OF NAVIGATION TECHNOLOGY SATELLITES TO THE GLOBAL POSITIONING SYSTEM

INTRODUCTION

The successful launch of Navigation Technology Satellite 2 (NTS-2) marks the beginning of a new era in navigation and timekeeping history. NTS-2 (figure 1) is the first NAVSTAR GPS [1] Phase I satellite. NTS-2 technological features include cesium frequency standards, a nickel-hydrogen battery, three-axis gravity-gradient stabilization with momentum-wheel unloading, control of the spacecraft orbit, laser retroreflectors, solar-cell experiments, radiation dosimeters, and a worldwide network for data acquisition. The satellite experiment has verified Einstein's relativistic clock shift.

NTS-2 is also the fourth in a series of NRL technology satellites (table 1) which have carried quartz [2], rubidium [3], and cesium [4] oscillators into orbit. The primary data type for all of the technology satellites has been precise time-difference measurements, which have been used for time transfer [5,6], navigation [7,8], and orbit determination.

Table 1 — NRL Technology Satellites

Satellite	Launch Date	Altitude (n.mi.)	Inclination (deg)	Eccentricity	Weight		Power (W)	Frequency	Oscillator	$\Delta f/f$ per day (pp 10^{13})	Range Error (m/day)
					(kg)	(lb)					
T-I	5-31-67	500	70	0.0008	40	85	6	UHF	Qtz	300	750
T-II	8-30-69	500	70	0.002	55	125	18	VHF/UHF	Qtz	100	75
T-III or NTS-1	7-14-74	7,400	125	0.007	295	650	100	UHF/L band	Qtz/Rb	5-10	12-24
NTS-2	6-23-77	10,900	63	0.0004	430	950	445*	UHF/L,L_1, L_2	Qtz/Cs	2	5
NTS-3	1982	10,900	63	0.001	490	1080	475*	UHF/L, L_1, L_2	Cs/H_2	0.1	0.25

*Beginning of life.

GPS LAUNCH PROCEDURE

The NAVSTAR Global Positioning System (GPS) is a DOD program designed to provide precise navigation to a wide variety of military and civilian users by means of a constellation of 24 satellites deployed in subsynchronous orbits (figure 2). The Navigation Technology Segment of GPS has been assigned the task of validating key concepts and hardware, with special emphasis on spaceborne clocks and atomic frequency standards.

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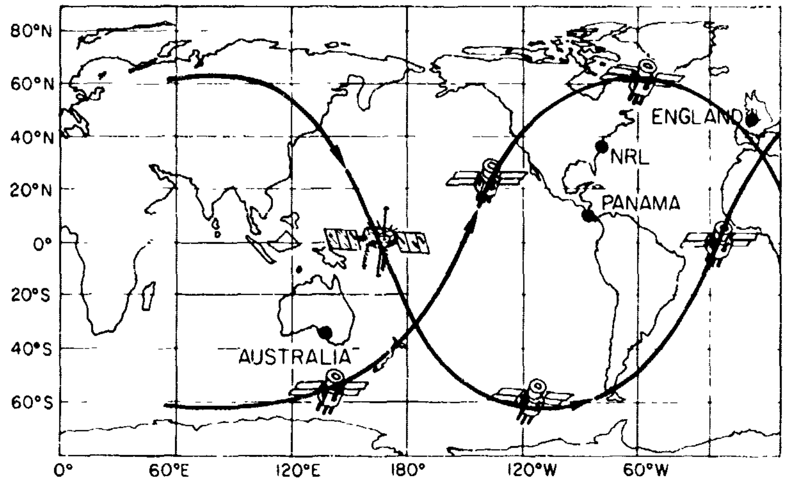

Fig. 2 — Possible orbit traces for the NAVSTAR GPS Phase 1 constellation. The Phase 1 constellation consists of the NTS-2 and five Navigation Demonstration System satellites. The final 24-satellite constellation will have similar orbit traces.

The GPS launch procedure (figure 3) places the spacecraft into a preassigned position in the GPS constellation. It is first launched into a high-eccentricity transfer orbit and then apogee-kicked into a low-eccentricity drift orbit. After the satellite drifts into position, its period is corrected for final constellation placement. The orbital period must be within an accuracy of 1 second of the specified value of 717.973 minutes (nearly 12 sidereal hours).

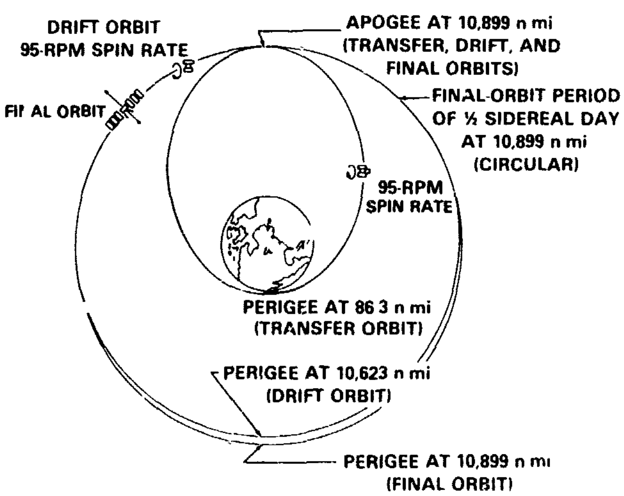

Fig. 3 — GPS launch procedure

The NTS-2 spacecraft was launched into the transfer orbit on June 23, 1977, at 0817 UTC (Universal Time Coordinated). First acquisition of signal was made by the NTS tracking station in Panama. NTS-2 was then acquired and tracked from Blossom Point, Md.

The initial network consisted of two of the NTS tracking stations (Panama and Chesapeake Bay, Md.), complemented with passive tracking by Blossom Point, Md., Millstone, Mass., and Sugar Grove, W. Va., and with optical tracking by the Range Measurements Laboratory, Patrick AFB, Fla. The network was coordinated by the NRL control center, as linked (figure 4) to the GPS master control station.

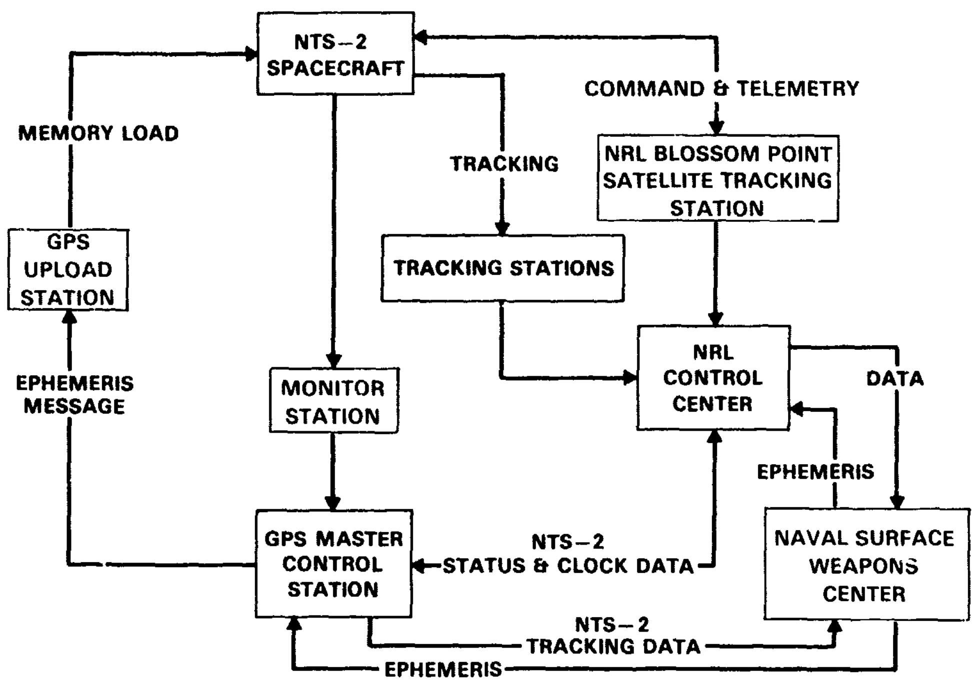

Fig. 4 — NTS-2 command and telemetry links

The prelaunch profile of the drift orbit (figure 5) was chosen to allow the ascending node of NTS-2 to drift eastward at 5 deg/day. The actual drift orbit (figure 6) had a larger drift rate than expected, resulting in NTS-2 reaching its preassigned position in the constellation of 28 ± 2 degrees west longitude in 5 days. Three velocity increments (figure 7), ranging from about 0.5 to 1 meter per second, were used to increase the spacecraft period. The final orbit, excepting small microthrusts, was achieved 15 days after launch. Three-axis gravity-gradient stabilization and solar-panel deployment were achieved within 18 days after launch.

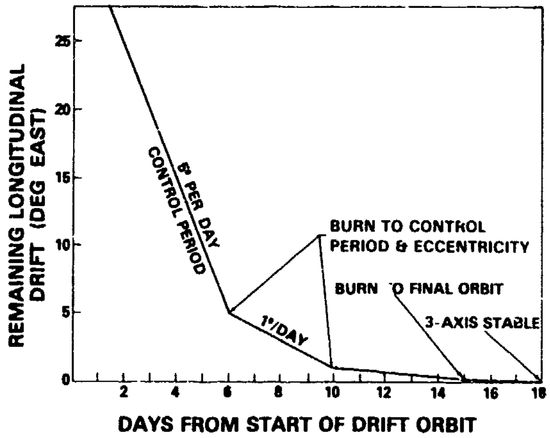

Fig. 5 — Prelaunch profile of the drift orbit

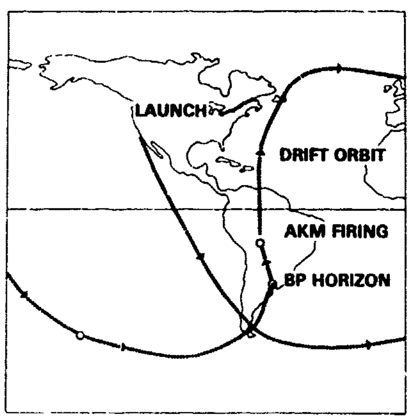

Fig. 6 — Scheduled NTS-2 drift orbit and, after drift and adjustments, the final orbit

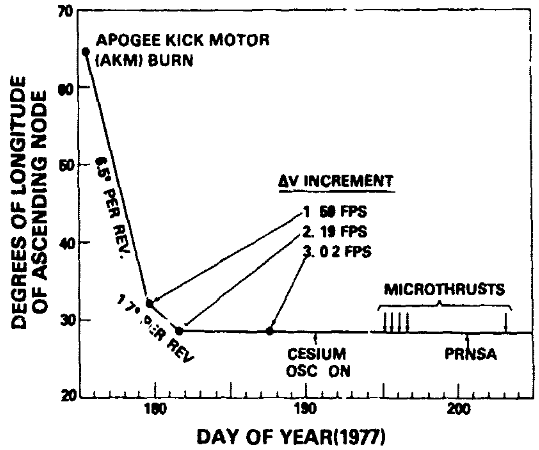

Fig. 7 — Inflight profile of the drift orbit

The final drift orbit of NTS-2 in the GPS Phase I constellation is given by figure 2. The locations shown for five Navigation Demonstration System satellites are also included.

NTS-2 TRACKING NETWORK

The original NTS tracking network consisted of a U.S. station at the NRL Chesapeake Bay Division in Chesapeake Beach, Md. (CBD), a U.S. station in the Panama Canal Zone (PMA), and overseas stations at the Royal Greenwich Observatory in England (RGO) and at the Division of National Mapping's Lunar Laser site in Australia (AUS). The U.S. stations are operated by Bendix Field Engineers; the overseas sites are operated by personnel from England and Australia. The network provides almost complete tracking coverage of NTS-2; figures 8 through 11 depict the portions of the NTS-2 orbit when the spacecraft is above the horizon from PMA, RGO, AUS, and CBD respectively. Figure 12 shows that only a small segment of the NTS-2 orbit is not observable by the NTS network.

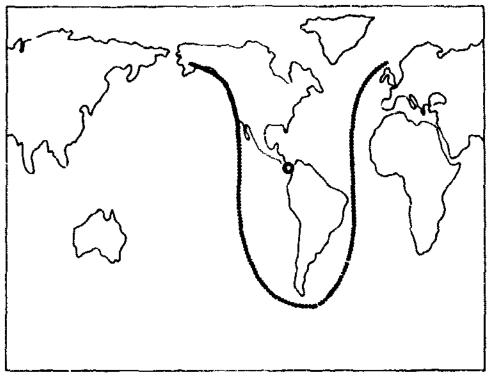

Fig. 8 — NTS-2 coverage from Panama

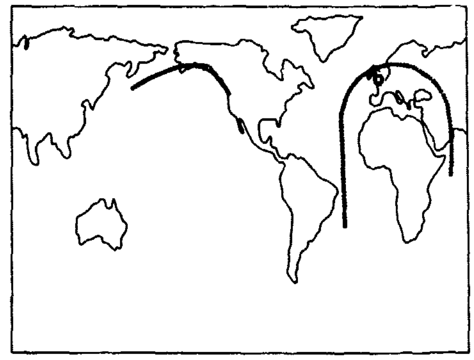

Fig. 9 — NTS-2 coverage from the Royal Greenwich Observatory

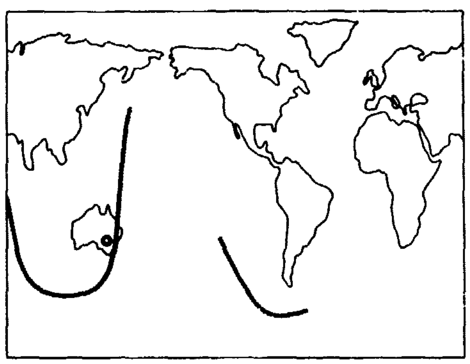

Fig. 10 — NTS-2 coverage from Australia

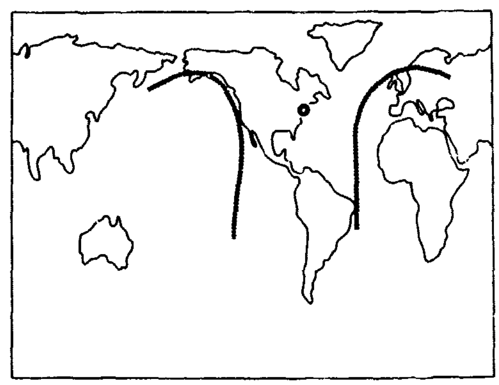

Fig. 11 — NTS-2 coverage from CBD

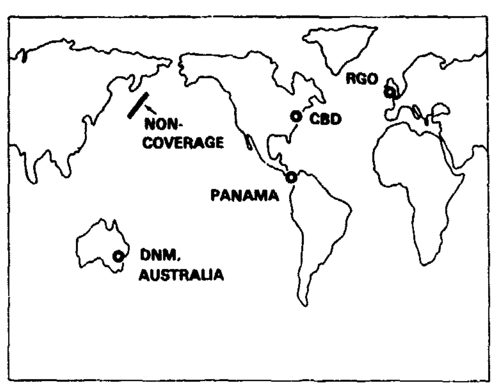

Fig. 12 — NTS-2 noncoverage from the four stations shown

PRECISE TIME AND FREQUENCY TRANSMISSIONS

Precise frequency signals for NTS-2 transmissions are obtained from one of two spacecraft-qualified cesium frequency standards built by FTS (Frequency and Time Systems, Inc.). The two cesium standards are of the same design; either may be selected as a precise frequency source. Each cesium standard may also be operated in a quartz oscillator mode, which requires less power. The reduced-power, quartz-only mode was used for the first 15 days after NTS-2 launch. The cesium standard was locked following solar-panel deployment.

NTS-2 timing information is continuously transmitted in two modes: a side-tone ranging system, called the Orbit Determination and Tracking System (ODATS), and a Psuedo Random Noise Subsystem Assembly (PRNSA). Time-difference measurements between the spacecraft clock and ground-station clocks are made through special receivers [9,10]. These measurements are then used to determine the spacecraft orbit [11], clock difference [12], frequency difference, and other parameters associated with GPS operation.

FREQUENCY DETERMINATION

The first FTS cesium standard to be used, designated as PRO-5, was locked up (figure 13) on the first attempt on day 190, 1977, at 1418 UTC following a VCXO frequency tune to bring the PRO-5 quartz oscillator frequency close to the cesium resonance frequency. Figure 14 shows a frequency offset of +442.5 pp 10^{12} with respect to the Panama clock. Inclusion of the Panama frequency offset of +0.6 pp 10^{12} produces an NTS measured value of +443.1 pp 10^{12}. Comparison of this value to the predicted value of the relativistic offset of +445.0 pp 10^{12} gives a difference of −1.9 pp 10^{12}.

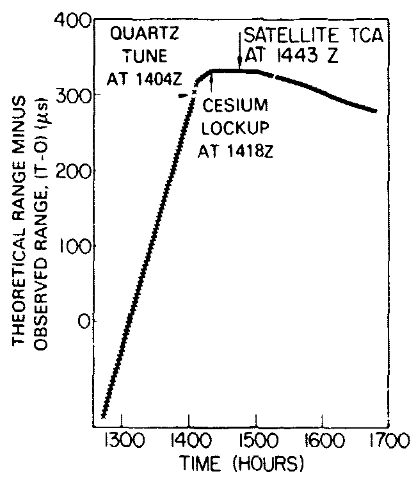

Fig 13 — Lockup of the cesium frequency standard on day 190 (July 13, 1977) The values (T - O) are used to determine the offset of the spacecraft clock with respect to the time scale determined by a three-clock ensemble at the Panama station.

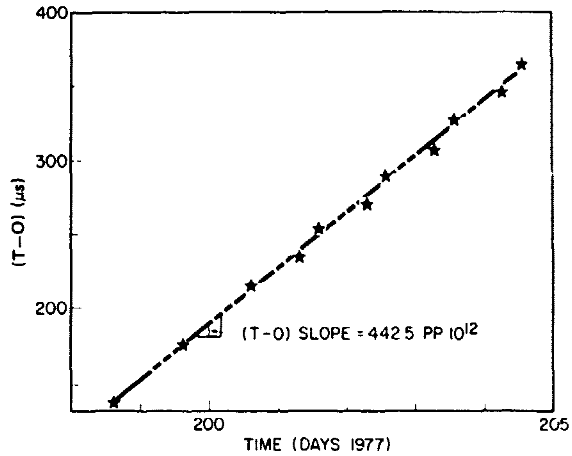

Fig 14 — Frequency offset with respect to the Panama time scale The offset is close in value to Einstein's predicted relativistic frequency determination of 445 0 pp 10^{12}

On day 215, 1977, the NTS-2 PRO-5 output signal was offset (figure 15) through the use of a frequency synthesizer. Closer frequency synchronization to the UTC rate was obtained by use of cesium C-field tuning. On day 287, 1977 (14 October), a C-field tune of six bits was applied. A frequency history of NTS-2 since launch is presented by figure 16; a split logarithmic scale is used so that positive and negative values of frequency offset with respect to UTC(USNO) may be included over a large range. Later analysis showed that an ensemble of cesium clocks was needed at the ground tracking sites to adjust the spacecraft clock to the accuracy of 1 pp 10^{13}.

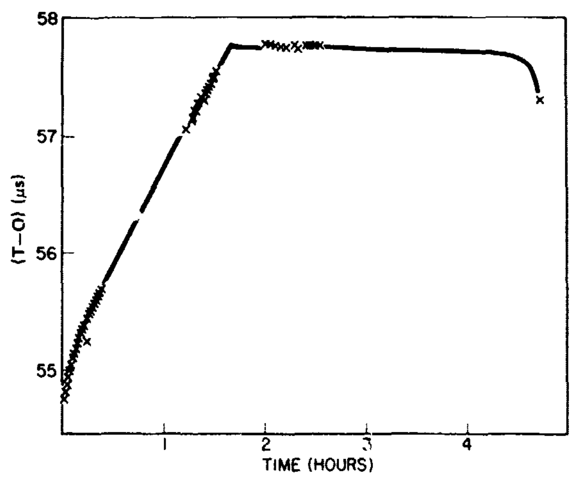

Fig. 15 — Effect of the correction on day 215, 1977, for the relativistic shift, as measured with respect to the CBD clock

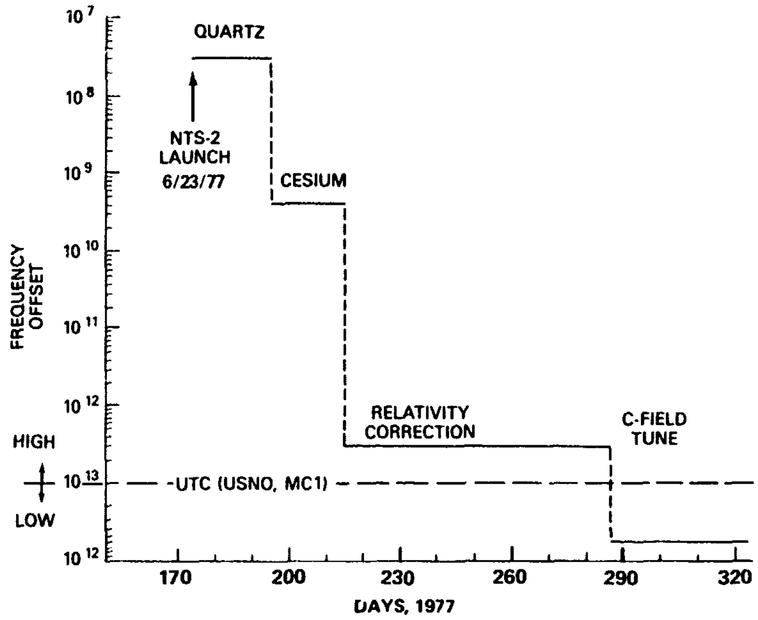

Fig. 1[illegible] - History of the NTS-2 frequency offset with respect to Master Clock 1 (MC1) of the U.S. Naval Observatory (USNO)

FREQUENCY RESULTS

Frequency [illegible] dard results from the NTS-2 cesium clock are presented in figures 17 and 18. In figure 1[illegible] [illegible] the preflight test results for up to a 1-day sampling time match closely [illegible] results available from sampling times of 1 day and longer [illegible] more complete analysis, reported in Ref. 13.

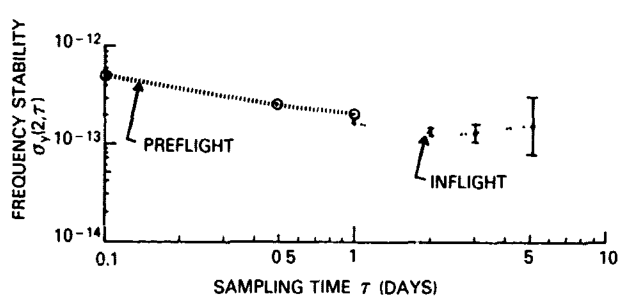

Fig. 17 — Stability of the NTS-2 cesium frequency standard, expressed using the measure $\sigma_y(2, \tau)$, which is the square root of the Allan variance

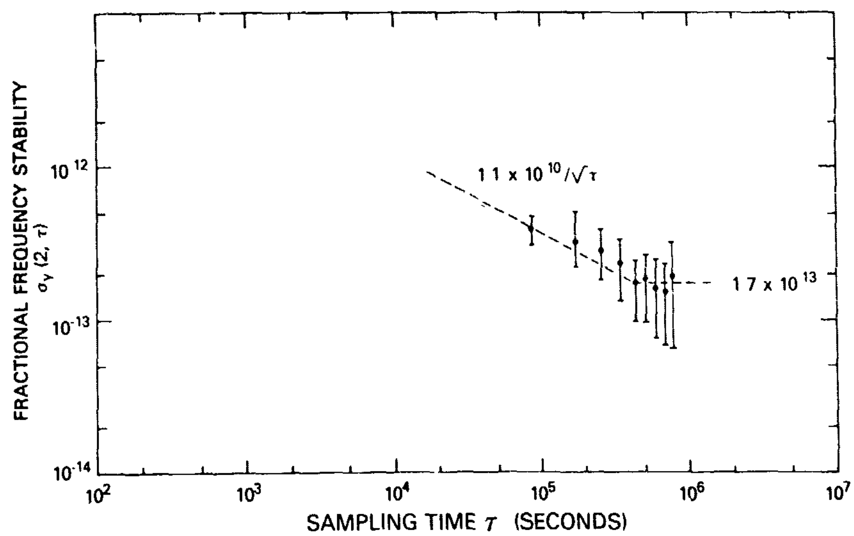

Fig. 18 — Analysis of the frequency stability of the NTS-2 cesium clock with respect to the time scale determined by the three-clock ensemble at the Panama Station

LASER ORBIT-VERIFICATION PROGRAM

A laser program using reflections from the NTS-2 retroreflectors has been started. This program will do the following:

- Resolve the problem of scale bias,
- Determine the long-range stability of the position of the tracking station,
- Make laser-network observations,
- Refine the coefficients of geopotential,
- Determine precise GPS orbits, and
- Evaluate the cesium frequency standard.

Figures 19 and 20 show the retroreflector elements for NTS-1 and NTS-2. Laser returns have already been obtained from the Mt. Hopkins, Arizona, site of the Smithsonian Astrophysical Observatory (SAO). Figures 21 and 22 present the residuals referenced to the NTS-2 orbit. The measured biases of 56 and 17 ns provide preliminary verification of the NTS orbit. The noise levels of 6 and 5 ns are typical of the expected laser-measurement noise level for this laser configuration; implementation of a shorter laser pulse should improve these results.

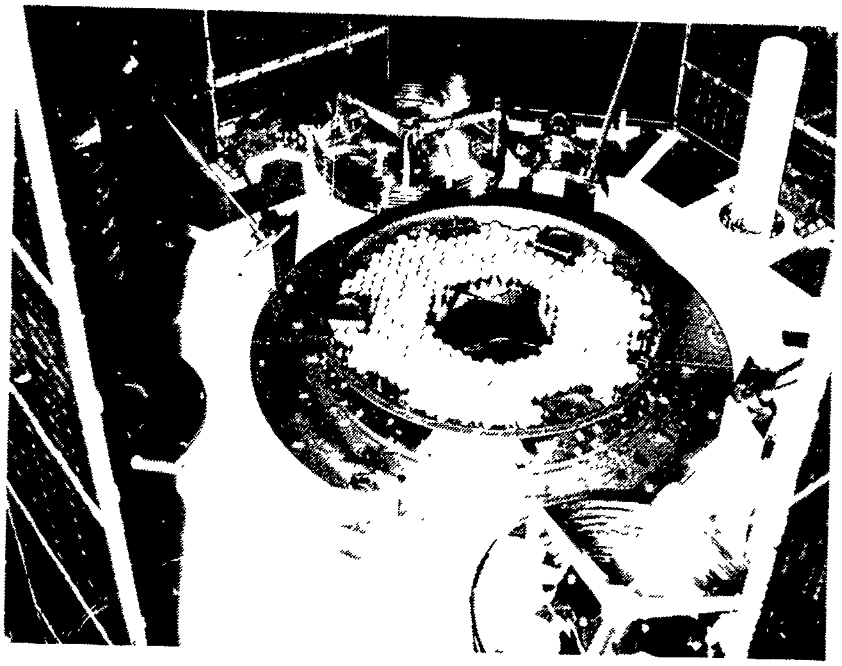

Fig. 19 — NTS-1 laser retroreflector

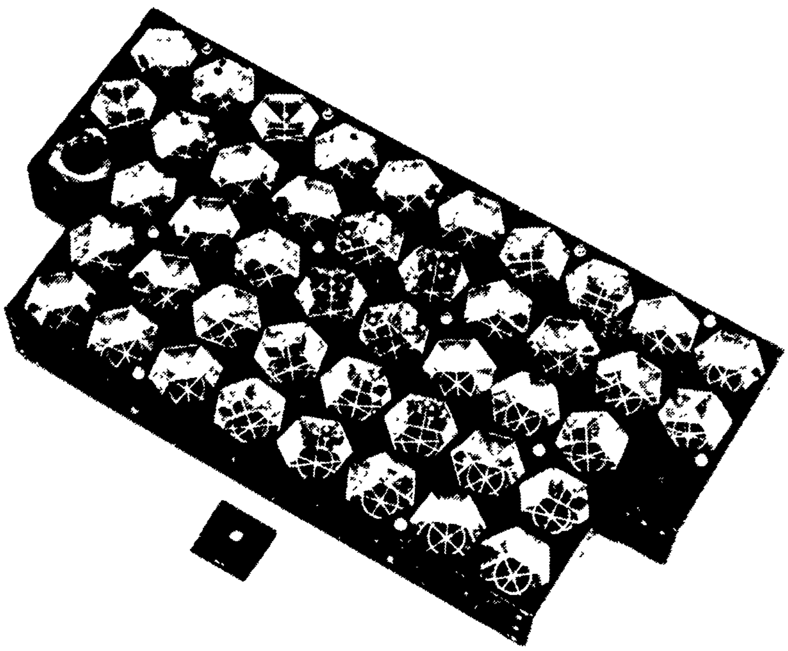

Fig 20 — NTS-2 laser retroreflector (The square object is a matchbook to show the size)

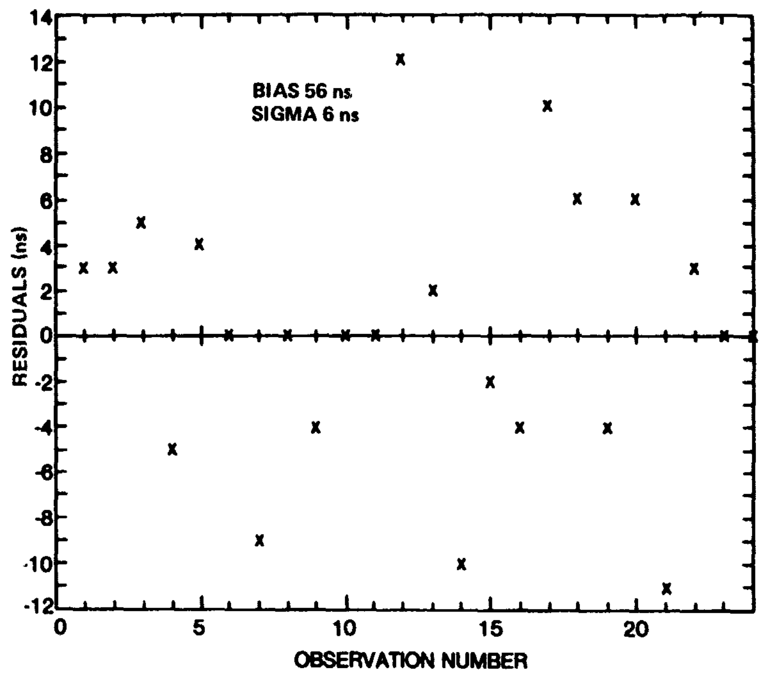

Fig. 21 — Laser observation residuals from the SAO Mt. Hopkins, Arizona, site for day 238, 1977, 0333 to 0403 hours

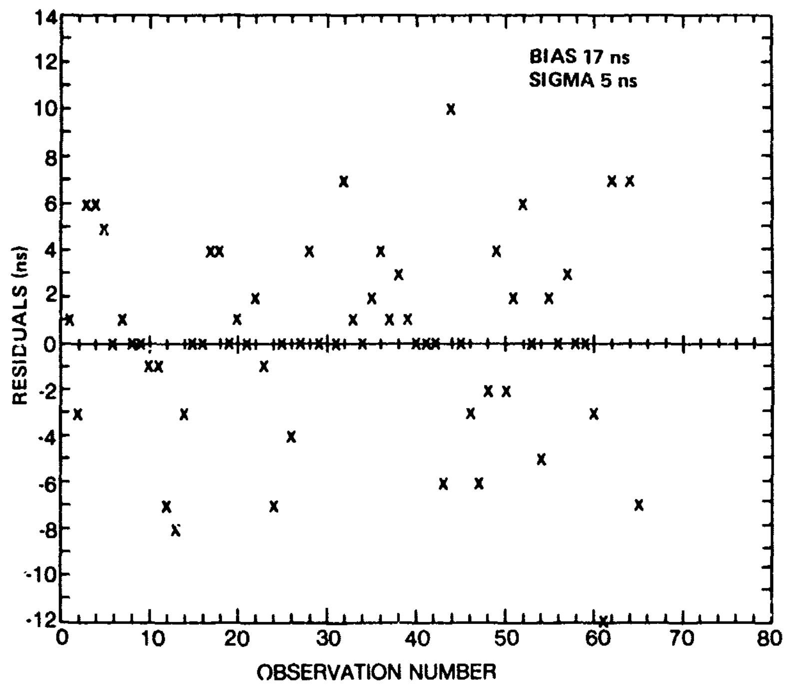

Fig. 22 — Laser observation residuals from the Mt. Hopkins site for day 241, 1977, 0320 to 0338 hours

TIME-TRANSFER EXPERIMENT

Precise time synchronization of remote worldwide ground clocks has been obtained using both NTS-1 and NTS-2 satellites. Figure 23 depicts the technique and the links which are used to relate a time difference, measured with respect to the satellite clock back to UTC(USNO). The time-transfer results are of interest to the precise time and time interval (PTTI) community but also are significant for the GPS community, because four simultaneous time transfers measured between a user and four GPS satellites form the basis of a GPS navigation and time synchronization.

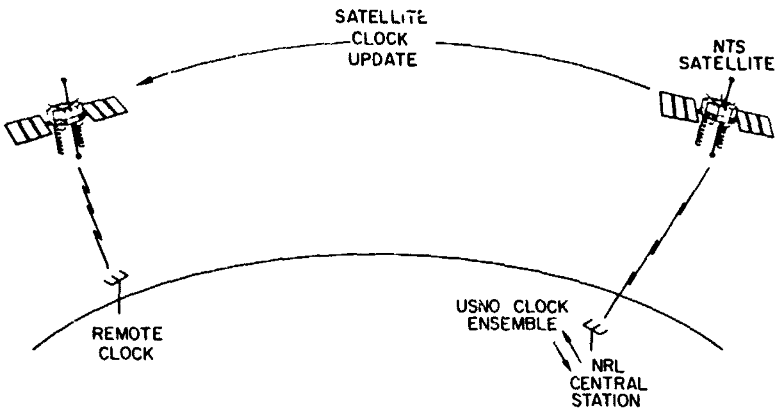

Fig. 23 — Station synchronization by time transfer using the Navigation-Technology Segment of the NAVSTAR GPS

From May through September 1978 a six-nation cooperative experiment was performed to intercompare time standards of major laboratories at the microsecond level using NTS satellites. NTS time-transfer receivers were installed at the Division of National Mapping (DNM), Australia; National Research Council (NRC), Canada; Royal Greenwich Observatory (RGO), England; Bureau International de l'Heure (BIH) and CERGA, France; Institute for Applied Geodesy (IFAG), West Germany; Radio Research Laboratory (RRL) and National Research Laboratory of Metrology (NRLM), Japan; and Goddard Space Flight Center (GSFC), National Bureau of Standards (NBS), Naval Research Laboratory (NRL), and Naval Observatory (USNO), United States.

To meet the objectives of the experiment, time differences were measured at the participating observatories, using a procedure that is as follows. The NTS network measurements are used to make an orbit. The central NTS tracking station has a time link to the Naval Observatory UTC(USNO, MC1) master clock. Then, using measurements taken with the NTS receiver at the remote observatory, the time-transfer value UTC(USNO, MC1) - UTC(remote, via NTS) is calculated. For a GPS user a similar procedure is followed using simultaneous measurements taken between the user and not one but four GPS satellites.

With the four GPS pseudo-range (time-difference) measurements taken at an unknown location, the user may solve for three three-position coordinates in addition to time offset with respect to GPS time. The goal for the NTS effort was to achieve worldwide time transfer with an accuracy of better than 1 microsecond.

Results are presented in Figures 24 through 31. Time comparisons from each station, as determined from measurements made through the NTS spacecraft, are verified by portable clock closures. Table 2 summarizes the results of this six-nation time synchronization campaign. It can be seen that submicrosecond worldwide accuracies have been achieved.

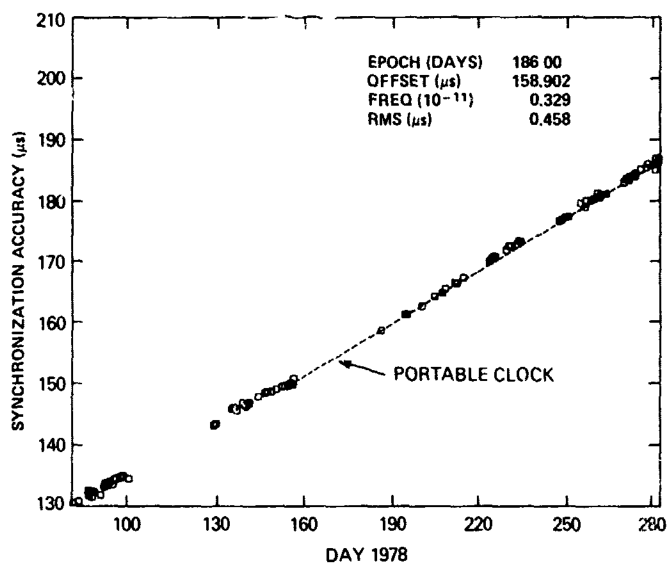

Fig. 24 — Time-transfer results from DNM (Australia)

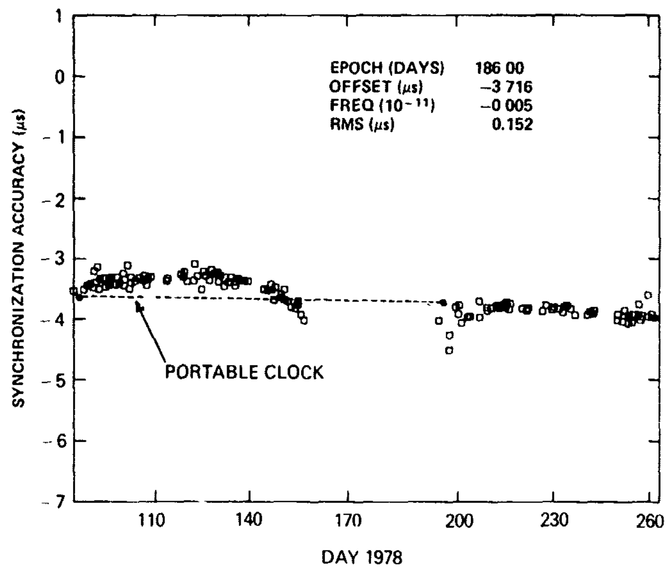

Fig. 25 — Time-transfer results from NRC (Canada)

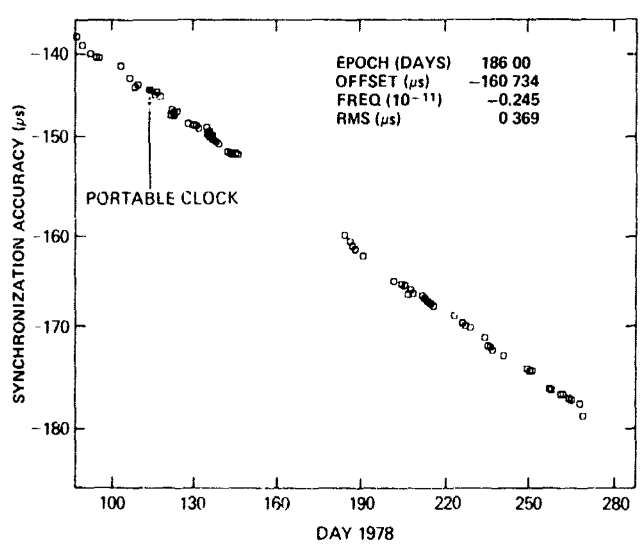

Fig. 26 — Time-transfer results from RGO (England)

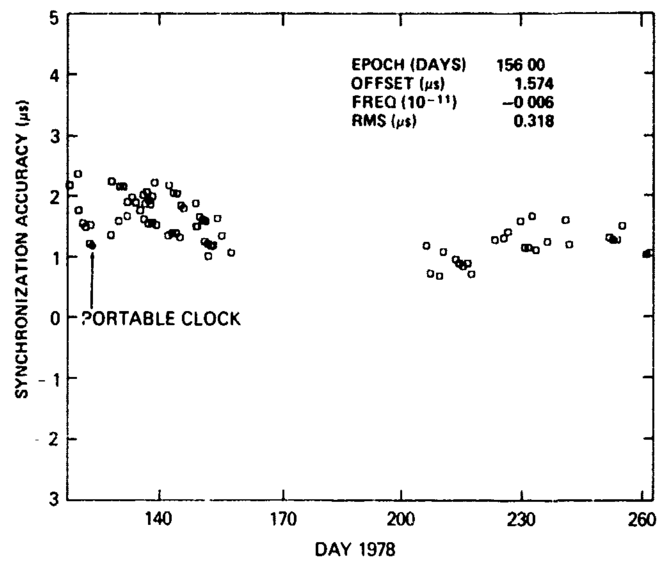

Fig. 27 — Time-transfer results from BIH (France)

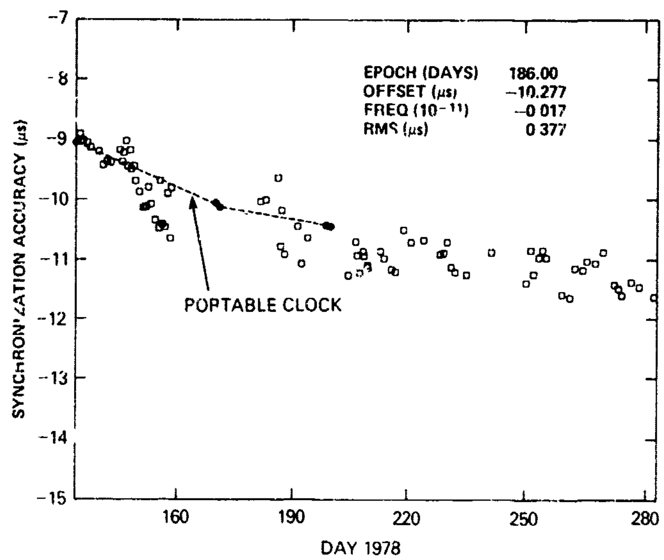

Fig. 28 — Time-transfer results from IFAG

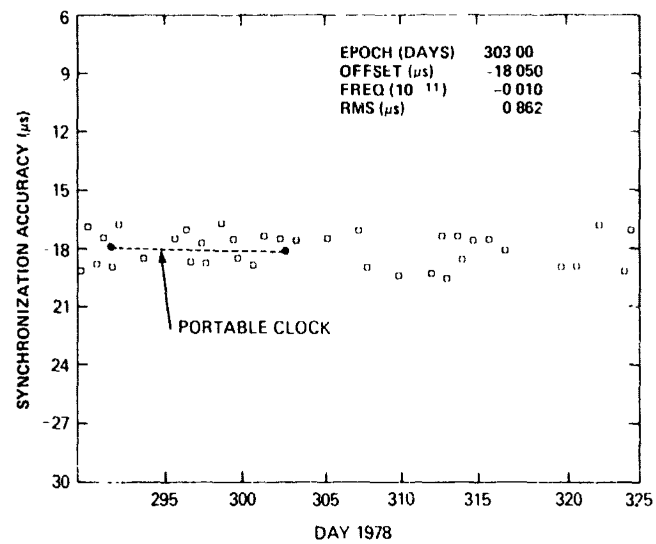

Fig. 29 — Time-transfer results from RRL (Japan)

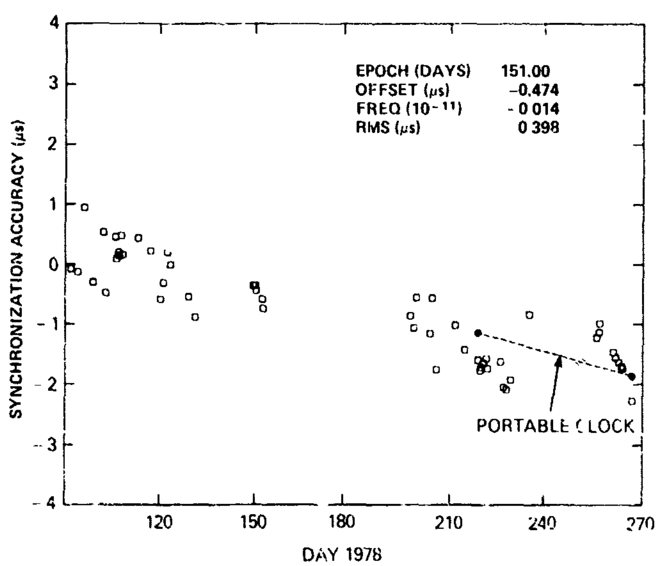

Fig. 30 — Time-transfer results from NBS

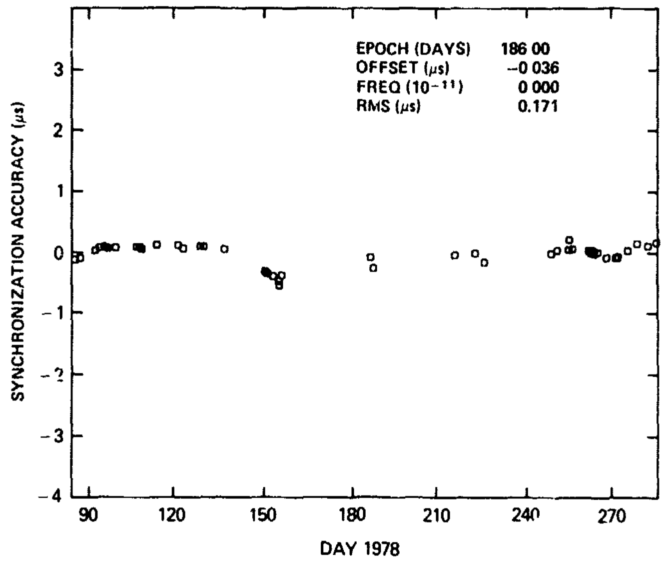

Fig. 31 — Time-transfer results from USNO

Table 2 — Accuracies Achieved in Synchronizing Portable Clocks by Time Transfer Using Navigation Technology Satellites

Station	Figure	Day (1978)	Portable-Clock Accuracy (μs)
DNM (Australia)	24	282	0.09
NRC (Canada)	25	186	0.01
RGO (England)	26	115	0.44
BIH (France)	27	124	-0.57
CERGA (France)	—	117	0.70
IFAG (West Germany)	28	199	0.03
RRL (Japan)	29	303	0.13
NRLM (Japan)	—	299	-0.53
NBS (United States)	30	221	0.19
USNO (United States)	31	186	0.04

CONCLUSION

The navigation-technology segment of the GPS has, so far, provided initial space-qualification tests of rubidium and cesium clocks. The segment also provided the original test of the GPS signals from space, verification of the relativity theory, measurement of radiation effects, laser retroreflector tracking, longevity effects on solar cells, and initial orbital calculations.

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